Distributed Raman Optical Amplification in Phase Coherent Transfer of Optical Frequencies

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Cecilia Clivati, Gabriele Bolognini, Davide Calonico, Stefano Faralli, Filippo Levi, Alberto Mura, and Nicola Poli

***Abstract*— We describe the application of Raman optical-fiber amplification (ROA) for the phase coherent transfer of optical frequencies in an optical fiber link. ROA uses the transmission fiber itself as a gain medium for bi-directional coherent amplification. In a test setup, we evaluated the ROA in terms of ON/OFF gain, signal-to-noise ratio, and phase noise added to the carrier. We transferred a laser frequency in a 200 km optical fiber link, and evaluated both co-propagating and counter-propagating amplification pump schemes. Then, we identified the occurrence of nonlinearities on the signal for non-optimized ROA gain. The frequency at the remote end has a fractional frequency instability of $3 \cdot 10^{-19}$ over 1000 s with the optical fiber link noise compensation.**

***Index Terms*— Coherent optical links, frequency comparisons of optical clocks, optical amplifiers.**

I. Introduction

NOWADAYS optical frequency standards are outperforming the primary cesium fountain clocks and are the most promising candidates for a redefinition of the second [1]. This improvement would be fruitless without a suitable method to compare such ultra-stable optical frequencies over long distances. Phase coherent optical fiber links can be used to this purpose [2]–[4], provided that the optical losses are compensated and the phase noise introduced by the fiber is cancelled. For the noise cancellation to be effective, light has to travel exactly the same path in both directions, with almost perfect bi-directionality [5]. To overcome losses while preserving bi-directionality, special bi-directional Erbium Doped Fiber Amplifiers (BEDFA) [3], [4], [6] and Fiber Brillouin Amplifiers (FBA) [4], [7] were developed.

Manuscript received March 24, 2013; revised May 29, 2013; accepted July 11, 2013. Date of publication July 15, 2013; date of current version August 6, 2013. This work was supported in part by Compagnia di San Paolo, MIUR under Grant PRIN09- 2009ZJJBLX, in part by Ente Cassa di Rispamio di Firenze, and in part by the EMRP program under Grant SIB02-NEAT-FT. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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Digital Object Identifier 10.1109/LPT.2013.2273269

In this Letter, we report on the first application of Raman Optical-fiber Amplification (ROA) for time-frequency metrology, in a laboratory optical fiber link with bi-directional phase-noise compensation.

ROA is based on the stimulated Raman scattering in silica fibers, a nonlinear effect generating a power transfer between two optical beams, the pump and the signal, through scattering with optical phonons [8], [9]. The gain is maximum when the signal light is downshifted $\sim$13.2 THz from the pump light, and the gain bandwidth is several THz wide around the gain peak. ROA also shows significant polarization dependence [10], so pump depolarization is required [11]. As in FBA, ROA has the relevant advantage of withstanding very high gain, without lasing or oscillations thanks to a distributed gain along the fiber [9], whereas in BEDFA Rayleigh scattering causes saturation of the gain medium and the onset of detrimental effects [6], compelling to keep the gain < 20 dB. ROA has lower efficiency than FBA: at 1.55 μm in standard single-mode fibers, the typical gain coefficient of ROA is $\sim 6 \cdot 10^{-13}$ m/W, whilst it is $\sim 5 \cdot 10^{-11}$ m/W in FBA [8]. Then, ROA pump power levels are higher than in FBA. In contrast, ROA is intrinsically bidirectional, i.e. it amplifies signals both co-propagating and counter-propagating with respect to the pump (hereafter indicated as co-pumped and counter-pumped), whilst FBA only amplifies counter-propagating signals. Also, having larger gain bandwidth than FBA, few THz against few MHz, ROA does not need a frequency control of the pump laser to ensure a stable gain, as it is required in FBA [7]. These features make ROA a very good candidate for simplifying long haul optical links, reducing the number of amplification stations along the way and increasing the overall link management and reliability.

ROA is employed for long-haul fiber-optic transmission [9], [12], but not yet in phase-coherent frequency metrology as an alternative to BEDFA or FBA, and there is not an experimental study of its added noise in optical links.

In this letter we evaluate the ROA gain, optical signal-to-noise ratio (OSNR) and performance in terms of added phase noise. We demonstrate the use of ROA on a 200 km link firstly in a single-pump scheme, then in a double-pump scheme. Finally, we identify the occurrence of nonlinearities on the signal for non-optimized ROA gain.

A careful design of our ROA scheme has been performed to avoid unwanted noise effects such as Kerr-based nonlinearities, pump-to-signal transfer of relative intensity noise (RIN), and double Rayleigh scattering. In particular, by solving a coupled differential equation system for

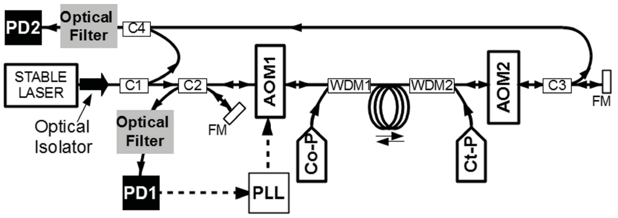

Fig. 1. Set up of the coherent fiber link with ROA. PD: Photodiodes, C: Couplers, FM: Faraday Mirrors, WDM: Wavelength Division Multiplexers, Co-P: Co-propagating Pump, Ct-P: Counter-propagating Pump, AOM: Acousto-Optic Modulators, PLL: Phase Locked Loop.

signal and pump power evolution with bi-directional pumping [8], we optimized the power levels of the input signal and the pump lasers. This ensures along the fiber an amplified signal power below the mW level, i.e. below the thresholds for modulation instability and stimulated Brillouin scattering (SBS) [8]. Many effects, critical in optical transmission with signal bandwidths >40 GHz, are expected to bring a smaller impact on the quasi-monochromatic sources used in metrology [8].

II. Experiment

A. Optical Instrumentation and Experimental Apparatus

To study the ROA in a coherent optical link, we set up a laboratory test-bed whose scheme is shown in Fig. 1. An ultrastable laser radiation at 1542 nm is generated by locking a fiber laser through the Pound−Drever−Hall technique to a Fabry−Perot high finesse cavity (120,000) made of Corning Ultra Low Expansion (ULE) glass. The resulting laser linewidth is smaller than 30 Hz (details in [13]), with OSNR ∼56 dB in 0.1 nm resolution bandwidth. Light is coupled into a standard SMF-28 single mode fiber, with a total length of up to 200 km, simulating a long-haul link from local to remote laboratory. The light power at fiber input is 0.5 mW; total losses due to fiber and connectors amount to ∼45 dB. To achieve phase noise cancellation, two acousto-optic modulators (AOM) are employed. AOM1 is placed before the fiber link and used as actuator to compensate the fiber phase noise. AOM2 is placed after the fiber link to shift the back-reflected radiation and allows to distinguish between the real signal (shifted by AOM2) and the backscattering from the fiber (not shifted). Photodiode PD1 is employed to detect the phase error from an interferometric scheme [13]; then, a phase-locked-loop (PLL) feeds AOM1 with a correction signal. The bandwidth of the PLL loop filter is 20 kHz, and a minimum round-trip optical signal power of about −70 dBm has to combine to the original light on PD1 to phase-lock the optical carrier. Photodiode PD2 is used to assess the link performance, comparing the phase noise of the signal at the remote end to that injected at the input by their beatnote.

Co- and counter-pumped ROA are implemented by coupling the pump into the fiber through wavelength-division multiplexers WDM1 and WDM2 respectively, that have 1.3 dB insertion loss. Two different pump lasers at 1450 nm are used. The first is a depolarized fiber Raman laser (FRL) delivering up to ∼800 mW into the fiber (OSNR > 50 dB in 0.1 nm resolution bandwidth). The other Fabry−Pérot laser (FPL) depolarized pump is composed of two polarization-multiplexed Fabry−Perot diode lasers, providing ∼260 mW (OSNR ∼58 dB in 0.1 nm resolution bandwidth) at the fiber input [14]. The pump laser depolarization is mandatory, as ROA exhibits a strong polarization-dependent gain (PDG). In particular, the Raman gain is maximum for co-polarized pump and signal, while it is minimum when pump and signal are orthogonally polarized. Therefore, care must be devoted to minimize gain fluctuations associated to fiber polarization mode dispersion (PMD). In the used optical fiber spools, the PMD coefficient is smaller than ∼0.2 ps/$\sqrt{}$km, and, to avoid PDG, our pump lasers (both the FRL and the FPL) are depolarized. For instance, in the case of the FPL, a pair of polarization-multiplexed laser diodes at the same wavelength leads to light output with orthogonal polarization components and eliminates PDG-related effects [11].

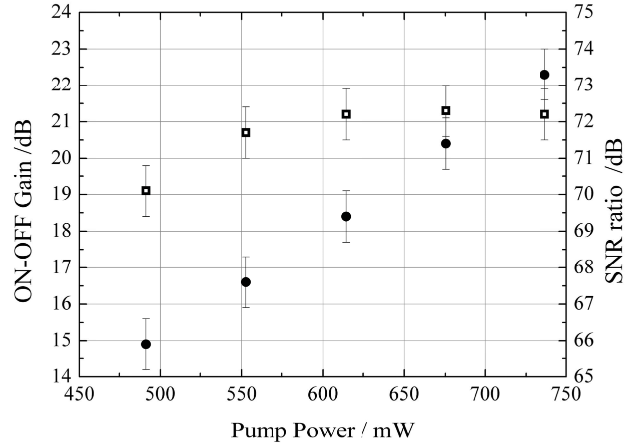

Fig. 2. ROA on-off gain (filled circles) and SNR in a 3 kHz bandwidth (empty squares) changing counter-propagating pump power.

Regarding the impact of RIN, pump-to-signal RIN transfer in Raman amplification could in principle impact on the intensity noise of the transferred signal, and then on the phase noise through Kerr effect. Counter-pumped ROA is known to be less affected by pump-to-signal RIN transfer than co-pumped ROA [15]. In fact, during counter-pumped amplification, the intensity noise transfer is averaged out by the large difference in the group velocities of pump and signal. This in principle leads to lower cross-talk levels and less stringent RIN requirements for the pump laser compared to co-pumping [15]. We employed higher-RIN FRL pump for counter-pumping, and lower-RIN FPL for co-pumping. The average RIN values at low frequencies (<10 MHz) for the pump lasers employed are ∼−140 dB/Hz for FPL (co-pump), ∼−110 dB/Hz for FRL (counter-pump) and <−141 dB/Hz for the signal. This leads to an expected added signal RIN of ∼−134.7 dB/Hz in co-pumping and ∼−95.3 dB/Hz in counter-pumping, whose cross-talk values are extremely low when integrated over the narrow signal bandwidth (30 Hz), and lead to negligible impairments of pump RIN in our scheme.

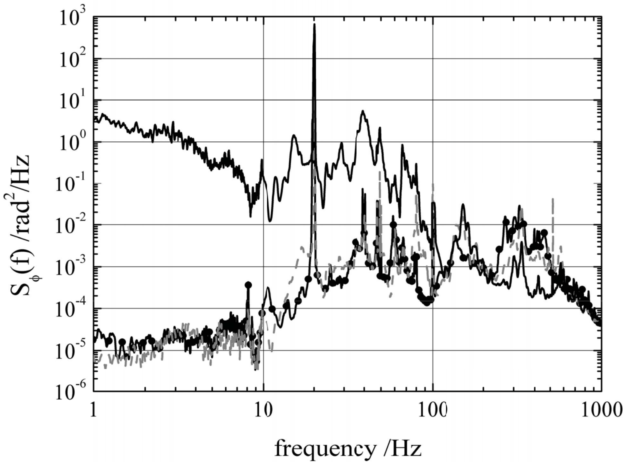

Fig. 3. Phase noise density S_ϕ(f) of the free running (solid black line) and compensated link at 100 km without amplification (dashed grey line) and with an amplification of 22 dB (solid black line, filled circles).

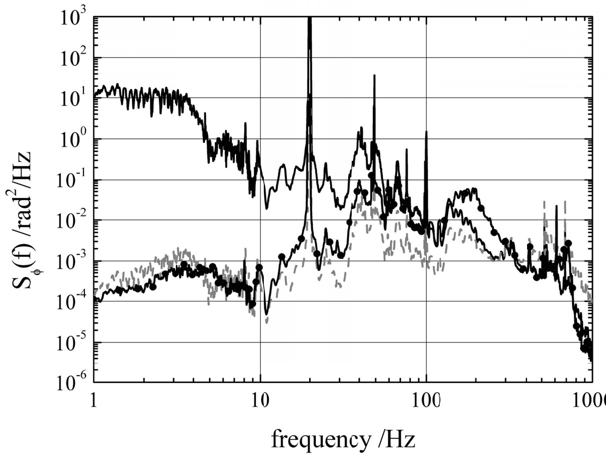

Fig. 4. Phase noise density S_ϕ(f) of the free-running link at 200 km (solid black line), compensated link at 200 km (black line, filled circles) and the expected residual noise at 200 km (grey dashed line) [5].

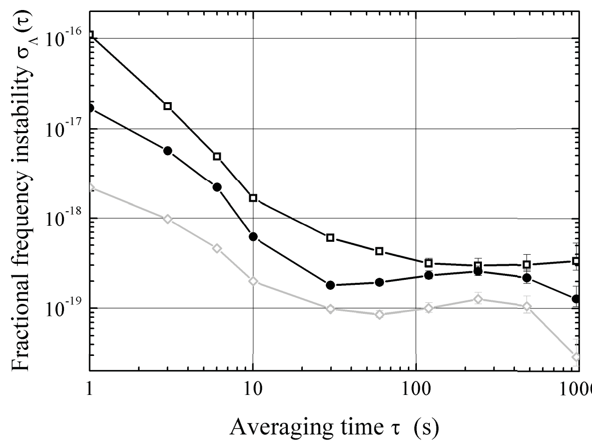

Fig. 5. Fiber link frequency instability on a 100 km link (filled circles), on the 200 km link using ROA (empty squares), and the interferometer noise floor (grey line, empty diamonds).

B. Measurements and Discussion

We initially evaluate the ROA impact with a counter-pump scheme, using the fiber Raman laser as pump; on-off gain and OSNR are measured using the link as a Mach−Zehnder interferometer, in which the amplified signal is in the measurement arm. We detect on PD2 the heterodyne beatnote between the amplified signal and the light from the short reference arm. Fig. 2 shows the measured gain and OSNR in a 3 kHz bandwidth after 100 km propagation versus fiber-coupled pump power. The gain increases with pump power and attains the maximum value of 22 dB, limited by the effective power available with our pump laser (800 mW). At high optical pump power, SNR is flat as expected, due to the amplified spontaneous emission [8]. For low optical power (pump radiation lower than 600 mW) the measured SNR shows a slight degradation due to the electrical noise on the photodiode. The absence of any induced SBS noise is also confirmed by optical spectrum analysis (OSA ANDO AQ6317B) of the transmitted signal and nearby frequency regions ($\sim$11 GHz frequency separation).

In these conditions, we measure the phase noise density S_ϕ(f) of the 100 km optical link with and without optical amplification, to assess possible effects of ROA on the link phase noise. Figure 3 shows the phase noise of the free running (solid black line) and compensated link without (dashed grey line) and with (black line, filled circles) an optical amplification of 22 dB. The spikes observed at frequencies within the link servo bandwidth (500 Hz) are mainly due to acoustic noise on the spooled fiber, particularly evident with the highest peak at 20 Hz. The residual noise of the compensated link agrees with the expected noise compensation limit due to the fiber delay [5], and there is no evidence of phase noise degradation on the compensated link in the two configurations.

We then increase the fiber length to 200 km. Fig. 4 shows the phase noise spectral density of the free-running link at 200 km (back line) and of the compensated link (black line, filled circles). The plot also shows the expected residual noise of the 200 km link (dashed grey line), evaluated considering the phase noise of the free running link and the fiber delay [5].

Link stability over long averaging times is calculated by counting the beatnote on PD2 with a high resolution Λ-type counter [16]. The data frequency instability $\sigma_\Lambda(\tau)$ can be converted into the Modified Allan deviation mod$\sigma_A(\tau)$ for common phase noises [17]. Fig. 5 shows $\sigma_\Lambda(\tau)$ of the link at 100 km (circles), at 200 km (squares) and of the interferometer without fiber spools (diamonds, grey line). Up to 20 s white phase noise is dominant, thus $\sigma_\Lambda(\tau) = 2\sqrt{2} \cdot \mathrm{mod}\sigma_A(\tau)$, whilst after 20 s frequency flicker noise is dominant and $\sigma_\Lambda(\tau) = \sqrt{2} \cdot \mathrm{mod}\sigma_A(\tau)$. At 200 km with counter-pumped ROA, the instability is $\sigma_\Lambda(\tau) \sim 3 \cdot 10^{-19}$ from 100 s to 1000 s. We can attribute this limit to random, uncompensated phase variations related to the fiber birefringence. Another effect impacting on instability can be given by the out-of-loop fibers, i.e. the fibers used to measure the phase stability prior to the coupler C4 and the Faraday Mirrors pigtails. These fibers have an overall length of less than 2 m and are expected to bring a contribution to the instability independent on the link length.

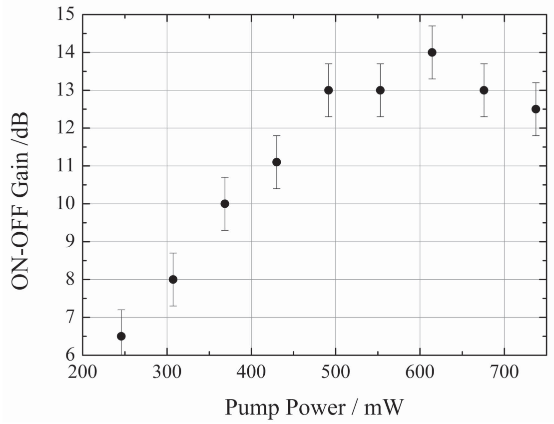

Fig. 6. On-Off Gain when the high-power fiber laser is used as a co-propagating pump. The gain is limited by nonlinear effects due to SBS.

These results show that counter-pumped ROA appears fully reliable for a phase coherent optical link.

To increase the span between intermediate stations, we test a double stage pump scheme, in which the Fabry−Pérot laser is coupled into the fiber as a co-pump through WDM1. ROA overall gain is then increased to 32 dB, equivalent to a single stage ROA with 1 W single counter-pump [12], limited by the power available with our Fabry−Pérot laser (260 mW). The double stage pump allows to overcome up to 61 dB losses in a single span, the maximum loss manageable by our setup.

To investigate the maximum usable pump power, the high-power fiber laser is then employed as co-pump (hence with high signal power levels) and the low-power laser diodes as counter-pump. Using high co-pump power levels, we observe strong degrading effects on the signal, posing a significant limitation to the use of ROA. However, this effect depends on the power level of the amplified signal, rather than on the amplification itself. Actually, in the co-propagating pump scheme, the amplified signal increases beyond the SBS threshold generating instability effects. In the counter-propagating scheme, the incoming signal is much lower due to the fiber losses, so the level of the amplified signal never exceeds the SBS threshold [8]. We measure the co-propagating signal gain, increasing the pump power while keeping a constant counter-pump gain of 9 dB, and with the input signal power at $\sim$0.5 mW. When the gain reaches $\sim$13 dB, the amplified signal achieves 10 mW, i.e. the SBS threshold. The amplification performance is then reduced with respect to the counter-pump scheme, and the 22 dB gain is not reached any more, as shown in Fig. 6. These effects, along with the Kerr-related nonlinearities and pump intensity noise transfer, can be reduced by a thorough design of the amplification scheme whenever intermediate ROA stations along an optical fiber link are required.

III. Conclusion

In conclusion, we demonstrate that ROA is suitable for optical amplification in phase coherent optical links, allowing the optical frequency transfer on 200 km in single fiber span, with a frequency instability of $3 \cdot 10^{-19}$ at 100−1000 s. ROA offers several advantages in terms of link maintenance and reliability with respect to other amplification techniques. It does not require pump frequency control, thanks to its wide gain bandwidth, and it has a distributed and higher gain than the BEDFA systems, as the fiber itself is used as a gain medium. However, particular care should be devoted to the design of links involving both counter- and co-pumping, to avoid nonlinear scattering affecting the ultimate performances.

We plan to investigate the use of Raman amplification on a 650 km coherent optical link that is under development between INRIM in Turin and LENS-UNIFI in Florence, Italy [18]. ROA could improve the present design, reducing the number of amplifiers, since at the moment nine BEDFA amplifiers are used. ROA could also bring benefits in case of extended, ultra-long link implementations.

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